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GULLY EROSION IN MANGATU FOREST, NEW ZEALAND, ESTIMATED FROM DIGITAL ELEVATION MODELS

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ABSTRACT

The methodology and errors involved in determining the amount of sediment produced during two (19·5 and 33·2 year) periods by 11 (*c*. 0·01–>0·20 km^2) gullies within a 4 km^2 area in the headwaters of the Waipaoa River basin, New Zealand, using sequential digital elevation models are described. Sediment production from all gullies within the study area was $0{\cdot}99\pm0{\cdot}03\times10^6$ t a^{-1} (2480 ± 80 t ha^{-1} a^{-1}) during the period from 1939 to 1958. It declined to $0{\cdot}62\pm0{\cdot}02\times10^6$ t a^{-1} (1550 ± 50 t ha^{-1} a^{-1}) during the period from 1958 to 1992, when many of the smaller gullies were stabilized by a programme of afforestation, which commenced in 1960. Both figures are very high by global standards. The two largest (the Tarndale and Mangatu) gully complexes together generated 73 and 95 per cent of the sediment in the specified time periods, but the latter amount is equivalent to only *c*. 5 per cent of the total annual sediment load of the Waipaoa River. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: digital elevation models; gully erosion; sediment production

INTRODUCTION

Gullies are relatively deep, unstable, eroding chanels that form at the head, side or floor of valleys where no well-defined channel previously existed (Schumm *et al*., 1984). In New Zealand's North Island gully erosion is widespread. It affects some 10 per cent of the land area and is predominantly associated with terrain underlain by argillite rocks of Cretaceous age (Eyles, 1985). Some of the most spectacular examples of gully erosion occur in the headwaters of the Waipaoa River basin, eastern Raukumara Range (Figure 1). Here the argillite rocks, which were crushed during emplacement of the East Coast Allochthon (Mazengarb *et al*., 1991), are particularly susceptible to acid sulphate weathering (Pearce *et al*., 1981). Most of the smaller gullies are linear features that occupy topographically convergent areas in otherwise unchannelled zero-order basins, while larger gullies have an amphitheatre-like form and engross virtually their entire drainage basin. The latter develop when gully erosion occurs in association, or as a complex, with mass movements, in which case fresh slides and flows are initiated as the gully inexorably cuts back into the disturbed terrain.

Among the most extensive and best known amphitheatre-like gullies are the Tarndale and Mangatu gully complexes, which are each *c*. 0·2 km^2 in area (Figure 2). Under the native forest cover, capacious mass movements and gullying were sustained by tectonic uplift (*c*. 0·01 m a^{-1} over the past 10^4 years), but it is thought that the gully complexes examined in this paper were initiated early this century as a result of increased runoff that occurred after the native forest cover was converted to pasture (Allsop, 1973). The clearances began in the 1880s and were completed by the 1920s. Anecdotal evidence suggests that the Tarndale gully complex was initiated on the site of a mass movement that formerly had occurred under the native forest cover, some 20 years after the forest had been cleared, in the winter of 1915 (Allsop, 1973; Gage and Black, 1979).

Gully erosion has long been considered to be the source of much of the sediment carried by the Waipaoa River (Hamilton and Kelman, 1952), which has been aggrading for much of this century and has one of the

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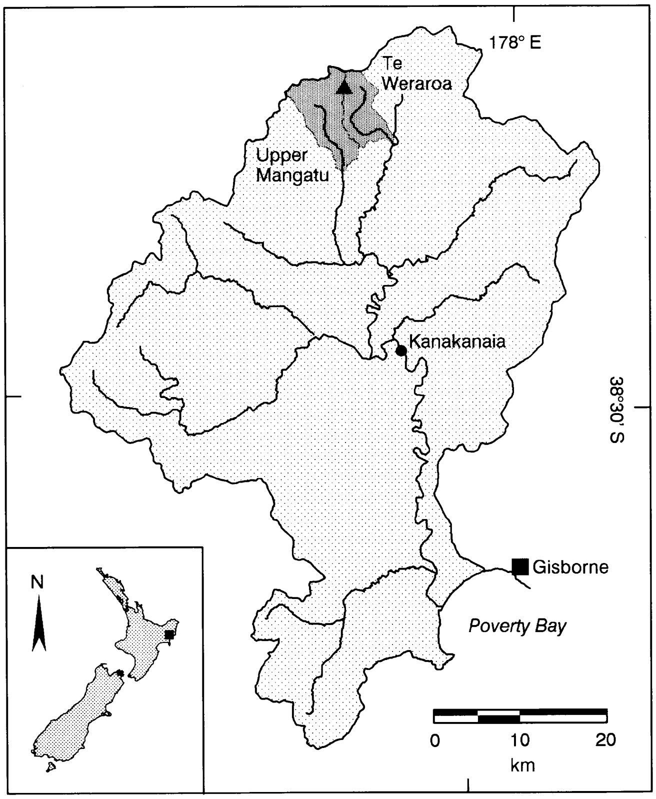

Figure 1. Waipaoa River catchment. The solid triangle marks the location of the Mangatu and Tarndale gully complexes, on the drainage divide that separates the Upper Mangatu and Te Weraroa subcatchments (delimited by dark stipple). The solid dot marks the location of the gauging station at Kanakanaia on the mainstem of the Waipaoa River

highest measured suspended sediment loads of any river in New Zealand (Hicks *et al*., 1996). Early attempts to control gully erosion in the headwaters of the Waipaoa catchment by check dams were largely ineffective, but post-1960 afforestation of the most severely eroded land in the critical headwater regions helped stabilize many active gullies and reduced the rate of gully formation (Allsop, 1973; Water and Soil Directorate, 1987). However, erosion in the amphitheatre-like gully complexes, where the bare head- and side-walls extended from the channel to the ridge top, was too far advanced to be mitigated by afforestation, and it is speculated that these gullies are now the principal source of sediment entering the river system (Water and Soil Directorate, 1987). Sediment generated within the Tarndale gully complex has a D_{50} of 1·4 mm, and 60 per cent is finer than 2 mm in diameter (Phillips, 1988). Large quantities of sediment appear to be moving out of the Tarndale and Mangatu gully complexes, but neither rates of erosion nor the relative contribution that the gully complexes make to the sediment load of the Waipaoa River have been quantified.

The contribution that gully erosion makes to sediment production has been evaluated using sequential aerial photography and orthodox photogrammetric techniques (Seginer, 1966; Dymond and Hicks, 1986; Poesen *et al*., 1996). In this paper, for the first time to our knowledge, area and elevation differences derived from high-resolution digital elevation models (DEMs) are used to estimate the amount of sediment contributed by gully erosion. We describe the methodology and errors involved in determining the amount of sediment produced by 11 gullies in the headwaters of the Waipaoa River basin, and assess the proportion of the total annual sediment load of the Waipaoa River supplied by the Tarndale and Mangatu gully complexes. Our data pertain to rates of sediment production, rather than sediment yields, because at present we have no means of reliably assessing sediment delivery ratios.

Figure 2. Tarndale gully complex and Te Weraroa Stream (foreground) in 1961 (Photo: J. H. Johns, 14 November 1961). The gully amphitheatre is *c*, 300 m deep and *c*. 500 m wide, and the width of the feeder channel at the head of the fan is *c*. 100 m

STUDY AREA

The gullies considered in this study are located within the upper Mangatu and Te Weraroa subcatchments, which together constitute 4 per cent of the 2205 km^2 Waipaoa River basin (Figure 1). These gullies vary in size from *c*. 0·01 to >0·2 km^2, and the drainage basins that support them range from a few thousand square metres to 0·45 km^2 in area. Most of the smaller gullies are elongate (linear), while the larger gully complexes have an amphitheatre-like appearance (Figure 3). The gullies occur in association with the Whangai Formation which is synonymous with the Mangatu Formation of Black (1980). The Whangai Formation comprises variably indurated, sheared and crushed, well-bedded, alternating light and dark grey siliceous mudstone and thin sandstone, and poorly bedded, pale grey calcareous mudstone of Late Cretaceous to Palaeogene age (Black, 1980; Mazengarb *et al*., 1991). Valley side slopes are *c*. 800 m long, with an average angle of 25°, and the ridge crests lie between 500 and 800 m above sea level (Pearce *et al*., 1981). Depending on altidue, the annual rainfall in the headwaters of the Waipaoa River basin is of the order of 1000 to 3000 mm (Hessell, 1980). Planting of the

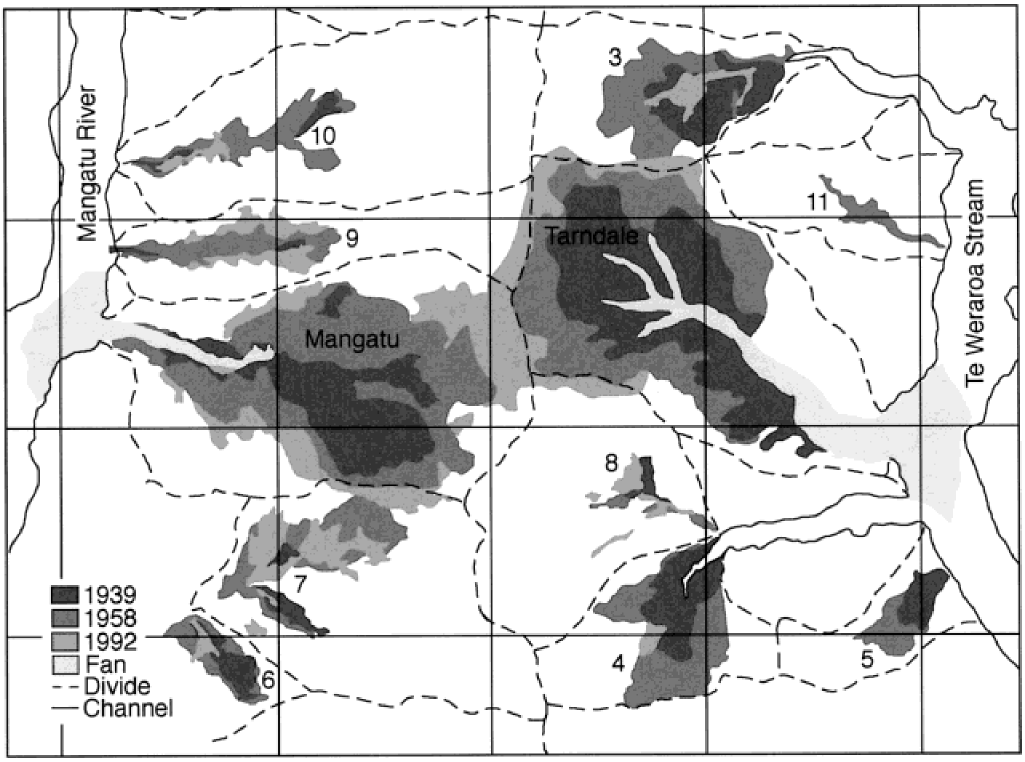

Figure 3. Extent of gullies within the study area in 1939, 1958 and 1992, drainage basin boundaries for 1958, and stream channel boundaries for 1992. The grid lines, which are oriented north–south and east–west, delimit areas of 0·5 km^2

Mangatu Forest commenced in 1960, and by 1970 the drainage basins of all the gullies examined in this paper had been reforested (Allsop, 1973).

DEM CONSTRUCTION

Three DEMs were constructed, on a 5 m grid, for a 4 km^2 area within Mangatu Forest that encompassed the Tarndale and Mangatu gully complexes and nine smaller gullies (Figure 3). Surface elevations were derived from 1:12 000 (2 June 1939), 1:18 000 (23 November 1958), and 1:15 000 (20 February 1992) scale stereo photographs. The 1939 photographs were the earliest available, the 1958 coverage was the best available for the period immediately prior to afforestation, and the 1992 photography contained surveyed ground control points.

Digital images were obtained by scanning contact diapositives of the 1958 and 1992 photography at 25 μm, and the larger scale 1939 photography at 50 μm. Image processing was undertaken using a commercially available software package (IMAGINE). Differentially corrected measurements with an accuracy of ±1·0 m provided ground control. These measurements were made with a global positioning system on stable point features, such as tree stumps, fence posts and road intersections, that could be located on the aerial photographs. For the 1992 photography, triangulation (x, y, z) adjustments to the ground control points never exceeded ±0·3 m. Triangulation adjustments typically were less than ±1·0 m for the 1958 photography, but were as much as ±3·0 m for the 1939 photography.

IMAGINE provides the capability to automatically collect a user-defined ground-space matrix of elevations from triangulated imagery. The algorithm used is classed as an area correlator which attempts to match similar patches or patterns of pixels. Where image matches are precise, high levels of accuracy can be achieved. For the present photography, when sub-pixel accuracy was achieved, point elevations were accurate to within ±1·8, ±1·3 and ±0·7 m for the 1939, 1958 and 1992 imagery, respectively. However, between 20 and 40 per cent of elevation measurements were interpolated during DEM construction because of low textural definition in some

regions of the photographs (e.g. on shadowed hillslopes), and consequently the overall error is somewhat greater.

Two sources of error occur in the elevation measurements: random errors are generated by imprecise pixel matching (analogous to landing the floating point in conventional photogrammetry); and systematic errors are generated by differences in triangulation and ground control. We evaluated the random and systematic error limits in elevation by comparing elevation differences over regions of stable terrain (usually interfluves or terraces), where no elevation change was expected to have occurred in the interval between (the 1939 and 1958) photography. In the absence of random and systematic errors, the mean and variance of differences in elevation between DEMs should be negligible. The mean and standard deviation of 5 m grid-spaced elevation differences were calculated for eight 0·01 km^2 control sites. The standard deviation of points typically was ≤2 m, indicating that 95 per cent of the points lay within ±4 m of the mean elevation difference for each control site. These differences are primarily attributable to random errors generated during pattern matching. The standard error of the mean for the control sites was 0·1 m.

The mean elevation difference for the control sites varied from −1 to −6 m across the 1939–1958 difference image. Thus there were significant systematic errors associated with this image; on average, the 1939 DEM was 3·5±0·3 m higher than the 1958 DEM. Because of these errors it was necessary to apply a correction to the mean difference in the elevation of each gully. These adjustments were based on the average of the mean elevation differences for either two or four control sites in the vicinity of each gully. The total elevation difference error (95 per cent range) was calculated as twice the square root of the sum of variances of the mean elevation difference for the gully and the adjacent control sites. Errors due to shading within individual gullies were estimated by applying the elevation difference for only the unshaded areas to the gully as a whole. This assumes that average erosion rates are no different between shaded and unshaded parts of a gully. For the largest gullies, DEM interpolation in shaded areas led to an overestimate in volumetric sediment yield (Table I) of 3–5 per cent. Overestimates may be as high as 70 per cent for very small gullies (*c*. 1 ha) with a high level of shading. However, the overall sediment production rates from these gullies indicate that this should not substantially change the total sediment yield from gullies in the study area.

We were unable to undertake a similar error analysis for the 1958–1992 elevation difference image because the encroaching forest cover confounded elevation measurements at many control sites. Overall, the 1992 DEM was higher than the 1958 DEM, and the few control sites that were not obscured by tree growth suggested a systematic error of 1·5±0·3 m.

Table I. Change in area, average difference in elevation, displaced sediment volume due to surface lowering and subsidence, and sediment production for the Tarndale and Mangatu gully complexes and the nine smaller gullies within the study area (see Figure 3 for locations) for the periods 1939–1958 and 1958–1992.

Gully	Area (km^2)			Δ elevation (m)		Δ volume (m^3)		Sediment production (t a^{-1} × 10^6)	
	1939	1958	1992	1939–58	1958–92	1939–58	1958–92	1939–58	1958–92
Tarndale	0·181	0·271	0·200	*	*	3 962 000	4 828 000	0·407±0·022	0·291±0·015
fan	0·043	0·074	0·098	7·4	8·5	−547 600	−833 000	−0·052±0·004	−0·046±0·0033
								0·355±0·022	0·245±0·015
Mangatu	0·095	0·247	0·272	*	*	3 120 200	5 024 800	0·320±0·017	0·303±0·016
fan	0·007	0·019	0·042	4·0	8·1	−76 000	−340 200	−0·007±0·00066	−0·019±0·0012
								0·313±0·017	0·284±0·016
3	0·046	0·086	0·009	9·5	**	817 000	–	0·084±0·0050	–
4	0·032	0·069	0·004	6·8	**	469 200	–	0·048±0·0032	–
5	0·010	0·018	**	9·0	**	162 000	–	0·017±0·0010	–
6	0·011	0·022	0·004	5·1	2·0	112 200	8 000	0·012±0·00089	<0·001±0·000127
7	0·009	0·062	0·033	9·0	7·7	558 000	254 100	0·057±0·0034	0·015±0·000978
8	<0·001	0·012	0·013	4·4	1·0	52 800	13 000	0·005±0·00056	0·001±0·00032
9	0·003	0·027	0·037	5·9	7·2	159 300	266 400	0·016±0·0012	0·016±−0·0011
10	0·009	0·037	0·002	5·3	3·5	196 100	7 000	0·020±0·0015	<0·001±0·00006
11	0·000	0·012	**	5·6	**	67 200	–	0·007±0·0006	–

* Elevation differs for the main gully and adjoining slopes (see Figure 4)
** Obscured by forest cover
The error limits are 95 per cent confidence limits (two standard errors from the mean)

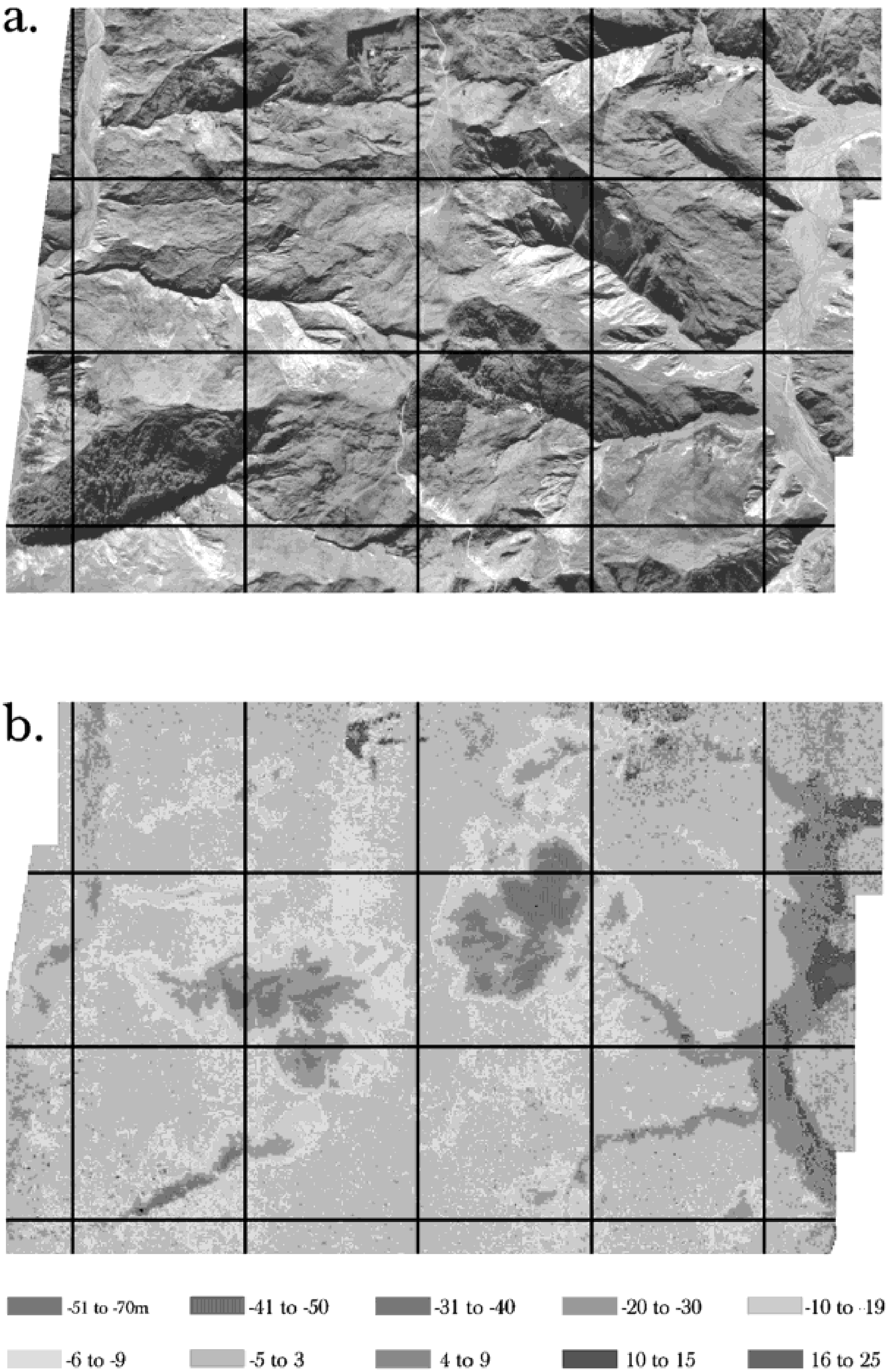

Figure 4. (a) Orthophotomap for 1939; (b) elevation difference map of the study area for the period 1939–1958. The grid lines, which are oriented north–south and east–west, delimit areas of 0·5 km^2

SEDIMENT PRODUCTION

Gullies deepen and enlarge over time. If the topography of a gully is known at two or more points in time, it is possible to ascertain the volume of the displaced sediment and, therefore, to estimate the amount of sediment the gully generates. We determined area and ground surface elevation differences from the DEMs and planimetrically corrected orthophotomaps (Figure 4a). Elevation differences (corrected for systematic errors) were calculated for 19·5 year (1939–1958) and 33·2 year (1958–1992) periods by subtracting elevations from the earlier date of photography from those from the later date (Figure 4b).

The elevation difference image shows that the pattern of erosion within the gullies is not uniform. Surface lowering typically was greatest along the gully axis and least around the periphery. The amount of surface lowering experienced at the centre of the Tarndale and Mangatu gully complexes was between 25 and 45 m in the period from 1939 to 1958 and between 45 and 70 m in the period from 1958 to 1992. Rates of channel incision during the two time periods ranged between 1·3 and 2·3 m a^{-1}. Smaller gullies exhibited a similar pattern of localized incision, but at rates that generally did not exceed 1 m a^{-1}.

For the period from 1939 to 1958, the average rate of surface lowering in gullies <0·04 km^2 in size was 0·23 to 0·31 m a^{-1}; for gullies between 0·06 and 0·09 km^2 in size it was 0·34 to 0·49 m a^{-1}; and for the Tarndale and Mangatu gully complexes the average rate of surface lowering was 1·1 and 0·8 m a^{-1}, respectively. By comparison, during the period from 1958 to 1992, within the Tarndale and Mangatu gully complexes the average rate of surface lowering was 0·79 and 0·77 m a^{-1}, and in the smaller gullies still visible in the 1992 photography it was <0·2 m a^{-1}. The displaced volume of sediment was determined from the average change in surface elevation experienced within each gully (Table I). However, because the encroaching forest sometimes obscured elevation changes caused by erosion on pre-existing gully surfaces, for the period from 1958 to 1992, the volume of material displaced from four gullies could not be determined reliably. Errors in the volume calculations accrued primarily from errors in elevation measurement. Inaccuracies in the sediment volume calculations due to random errors in elevation were minimal; systematic errors were of primary concern because, unlike random errors, they do not cancel out when the average surface elevation is calculated from a large number of points. We determined the volume error limits by multiplying the error in mean elevation difference for each gully by its area. In the absence of any information about spatial variations in the *in situ* dry bulk density of the weathered argillite, we assigned an arbitrary error (95 per cent) of ±100 kg m^{-3} to the value of dry bulk density (2000 kg m^{-3}) used to compute the mass of the eroded material.

Sediment production from the Tarndale gully complex was $0{\cdot}407 \pm 0{\cdot}022 \times 10^6$ t a^{-1} in the period from 1939 to 1958, and $0{\cdot}291 \pm 0{\cdot}015 \times 10^6$ t a^{-1} in the period from 1958 to 1992 (Table II). During the same time periods, sediment production from the Mangatu gully complex also declined from $0{\cdot}320 \pm 0{\cdot}017 \times 10^6$ to $0{\cdot}303 \pm 0{\cdot}016 \times 10^6$ t a^{-1}. For the periods from 1939 to 1958 and from 1958 to 1992, the amount of sediment produced from the remaining gullies was $0{\cdot}266 \pm 0{\cdot}017 \times 10^6$ and $0{\cdot}033 \pm 0{\cdot}003 \times 10^6$ t a^{-1}, respectively. Both the two large gullies thus generated a greater volume of sediment that the small gullies combined. All of the gullies have similar morphology, but sediment production per unit area increases with gully size because the average rate of vertical erosion also increases (Table II). Sediment production per unit area from gullies also appears to be greater during the expansion phase of gully development (1939–1958), compared to the later period when the gullies had stabilized or decreased in size (area) because of reforestation (1959–1992). The reduced sediment output from gullies during the latter measurement period probably is not simply a function of reduced gully area, but also of changes in weathering rates and the action and type of dominant erosion process(es).

A proportion of the sediment generated by gullies goes into storage, as is evidenced by the increased elevation of fan surfaces (Figure 4b). The mass of the accumulated sediment was computed using a dry bulk density of 1840 kg m^{-3} (R. C. DeRose, unpublished data). Net aggradation on the Tarndale fan was $0{\cdot}052 \times 10^6$ and $0{\cdot}046 \times 10^6$ t a^{-1} for the periods from 1939 to 1958 and from 1958 to 1992, respectively. These amounts represent 13 and 16 per cent of the sediment produced by the Tarndale gully complex during these periods. Aggradation on the Mangatu fan was $0{\cdot}007 \times 10^6$ t a^{-1} in the period from 1939 to 1958, and $0{\cdot}019 \times 10^6$ t a^{-1} in the period from 1958 to 1992. These amounts accounted for 2 and 6 per cent of the sediment produced in Mangatu gully complex during the respective time periods. The shorter and steeper feeder channel leading from the Mangatu gully complex thus afforded less opportunity for sediment storage than the longer and wider channel

Table II. Sediment production from individual gullies for specified time periods

Period	Gully	Mean area (ha)	Sediment production ($t\,a^{-1} \times 10^6$)	Error
1939–1958	TARNDALE	22·60	0·407	±0·022
	MANGATU	17·10	0·320	±0·017
	3	6·60	0·084	±0·005
	4	5·05	0·048	±0·003
	5	1·40	0·017	±0·001
	6	1·65	0·012	<±0·001
	7	3·55	0·057	±0·003
	8	0·65	0·005	<±0·001
	9	1·50	0·016	±0·001
	10	2·30	0·020	±0·002
	11	0·60	0·007	<±0·001
1958–1992	TARNDALE	23·60	0·291	±0·015
	MANGATU	25·95	0·303	±0·016
	6	1·30	0·001	<±0·001
	7	4·75	0·015	<±0·001
	8	1·25	0·001	<±0·001
	9	3·20	0·016	±0·001
	10	1·95	0·001	<±0·001

The error limits are 95 per cent confidence limits (two standard errors from the mean).

draining the Tarndale gully complex. Sediment generated by these two large gully complexes enters Te Weraroa Stream and the Mangatu River, respectively (Figure 1). Cross-section surveys indicate that both channels became overloaded and aggraded throughout the period 1948 to 1988 (Figures 2 and 4b). In Te Weraroa Stream the rate at which sediment accumulated in the channel was at a maximum in the period from 1948 to 1960, it declined throughout the period from 1960 to 1975, and there was little change in storage after 1975 (Banbury, 1996).

The mean annual suspended sediment load of the Waipaoa River at Kanakanaia (Figure 1), where measurements of suspended sediment discharge have been made since 1960, is *c*. $10{\cdot}7 \times 10^6\,t\,a^{-1}$ (Hicks *et al*., Submitted). The average bedload yield (estimated using Wilcock's (1998) modified Parker–Einstein formula) amounts to a small fraction (<1 per cent of the Waipaoa's suspended load. Thus, in the period from 1958 to 1992, the Tarndale and Mangatu gully complexes each generated the equivalent of 2–3 per cent of the total annual suspended sediment load at Kanakania. Because the amount of in-channel storage in Te Weraroa Stream has changed over time, the relative contribution of sediment from the Tarndale gully complex to the sediment load of the Waipaoa River (which is attenuated by storage in the fan and channel system) will probably also have changed. Compared to the period from 1939 to 1958, the proportion of sediment going into storage on the Tarndale fan in the period from 1958 to 1992 increased. However, surveys of the fan undertaken since 1982 indicate that its size has not changed appreciably in recent years (Banbury, 1996). Thus, although the total amount of sediment generated by gully erosion has declined with time, the decline in the amount of sediment that goes into storage along Te Weraroa Stream suggests that the proportion of the sediment generated by the Tarndale gully complex that exits the catchment is probably greater now than it was in the past.

CONCLUSION

The total contribution of gully erosion to sediment production in the $4\,km^2$ study area was $0{\cdot}99 \pm 0{\cdot}03 \times 10^6\,t\,a^{-1}$ ($2480 \pm 80\,t\,ha\,a^{-1}$) in the period from 1939 to 1958 and $0{\cdot}62 \pm 0{\cdot}02 \times 10^6\,t\,a^{-1}$ ($1550 \pm 50\,t\,ha\,a^{-1}$) in the period from 1958 to 1992. An unknown proportion of this material is stored in the gully fans and channels. The decline in sediment production is due to gully stabilization effected by afforestation, but the sediment production rates remain very high by global standards (cf. Milliman and Syvitski, 1992; Walling and Webb, 1996). Currently, however, the Tarndale and Mangatu gully complexes each generate only 2–3 per cent of the Waipaoa River's annual sediment load. These spectacular gully complexes, therefore, do not appear to dominate the sediment budget of the Waipaoa River. This is because greater contributions are made by the numerous contemporary

gullies in other parts of the Mangatu Forest, and/or by diverse sources elsewhere in the Waipaoa River basin. Indeed, the amount of sediment contributed to the river system from extensive mass movements (e.g. earthflows and slumps) and from surface erosion processes in other parts of the catchment, though unquantified, is thought to be considerable. At present, as much as 33 per cent of the Waipaoa River's suspended sediment load may be generated in the 175 km^2 Waingaromia subcatchment (cf. Griffiths, 1982). It is also known that in 1939, when the main gully in the Tarndale gully complex occupied an area of *c*. 0·064 km^2, the collective area of other active gullies within Mangatu Forest amounted to 2·95 km^2. At the peak of gully development (*c*. 1960) the main gully constituted only *c*. 2·5 per cent of the collective area of all actively eroding gullies in the forest (M. Marden, unpublished data). Therefore, although the amount of sediment generated by gullies elsewhere in Mangatu Forest is unknown, it appears unlikely that the Tarndale and Mangatu gully complexes, neither individually nor collectively, have ever dominated the sediment budget of the Waipaoa River basin.

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